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FINAL CONTRACT REPORT

ULTRAVIOLET ABSORPTION EXPERIMENT

MA-059

University of Pittsburgh

This report is submitted to complete the obligations of the University of Pittsburgh under contract NAS 9-13803.

Preflight activities and results were described in reports submitted August 1974, April 1975, June 1975 and July 1975. The experiment and flight results were described in the Preliminary Science Report and updated in the Summary Science Report.

Planned scientific publications relating to the experiment include:

- (a) The enclosed paper entitled "O(³P) and N(⁴S) Density Measurement at 225 km by Ultraviolet Absorption and Fluorescence in the Apollo-Soyuz Test Project" which was submitted to Geophysical Research Letters in December 1976;
- (b) a longer, detailed version of the same work which is to be submitted to the Journal of Geophysical Research; and
- (c) a paper by W. T. Rawlins and F. Kaufman dealing with the characterization of optical properties of O- and N-resonance lamps which is in preparation now.

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O(³P) and N(⁴S) Density Measurement at 225 km by Ultraviolet Absorption
and Fluorescence in the Apollo-Soyuz Test Project

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Abstract. The densities of O(³P) and N(⁴S) at 225 km were determined during the Apollo-Soyuz Test Project by a resonance absorption-fluorescence technique in which OI and NI line radiation produced and collimated on board the Apollo was reflected from the Soyuz back to the Apollo for spectral analysis. The two spacecraft maneuvered so that a range of observation angles of $\pm 15^\circ$ with respect to the normal to the orbital velocity vector was scanned. The measurements described here were made at night, July 19, 1975, on two consecutive orbits at spacecraft separations of 150 and 500 m. The resulting relative counting rates as function of observation angle were compared to calculated values to determine $[O] = 1.15 \times 10^9 \text{ cm}^{-3} \pm 30\%$, and $5.6 \times 10^6 \text{ cm}^{-3} \leq [N] \leq 11.2 \times 10^6 \text{ cm}^{-3}$. The [O] value agrees with mass spectrometric measurements made under similar conditions; the [N] value is in good agreement with other measurements and suggests a smaller diurnal variation than is predicted by present models.

Introduction

In the Ultraviolet Absorption Experiment (UVA, Experiment MA-059) of the Apollo-Soyuz Test Project (ASTP), ground-state atomic oxygen and atomic

nitrogen densities were measured at orbiting altitude (225 km) by atomic absorption spectroscopy between the two spacecraft. This complex resonance line absorption and fluorescence experiment required the presence and relative maneuverability of both the Apollo and Soyuz. OI and NI line radiation emitted by r.f. discharge lamps on the Apollo was collimated, beamed to the Soyuz, reflected from a retroreflector array on the Soyuz, and spectrally analyzed and measured on the Apollo. This note briefly describes the experiments and presents some of its preliminary results.

Principle of Experiment

The geometry of the optical transmitting and collecting system is shown in Figure 1. OI and NI line radiation was produced in separate glow discharge lamps by r.f. excitation (~ 230 MHz, ~ 4 W) of a low pressure (4-7 torr) He discharge containing small amounts of oxygen or nitrogen. The oxygen and nitrogen concentrations (and hence the optical thicknesses of the plasmas) were controlled by a balance between thermistor-regulated heating of appropriate chemical source compounds (KMnO_4 and NaN_3) and gettering (Ba). The radiation from each lamp was collimated by a concave mirror (5.7 x 3.3 cm) to a beam spread of $\sim 3^\circ$ and directed toward the Soyuz. The light was reflected back to the Apollo by one of three retroreflector arrays (55 cm² area) mounted on the Soyuz. It was then reflected by a plane collecting mirror (5.5 x 3.7 cm) to a concave mirror which focussed it onto the entrance slit of a 0.75-meter Fastie-Ebert scanning monochromator equipped with a solar-blind photomultiplier. All optical surfaces were coated with MgF_2 . The retroreflectors were sealed with protective covers until the time of the experiment. The Apollo optical system and spectrometer were protected by a door which was closed except during periods of external data collection.

Two line multiplets were used for each species in the measurements: one which was strongly absorbed by the ground state and one which was not. Thus the ground state species $O(^3P)$ and $N(^4S)$ were probed by the OI 130.4 nm ($^3S - ^3P$) and NI 120.0 ($^4P - ^4S^0$) triplets, respectively, whereas the experiment geometry and mirror reflectivities were monitored by the forbidden OI 135.6 nm ($^5S - ^3P$) doublet and by the NI 149.3 nm ($^2P - ^2D^0$) doublet. The line spectrum from 120.0 to 149.3 nm was scanned every 12 seconds through 1.5 nm ranges centered on each of the above four transitions with a bandwidth of 1.15 nm. Each lamp was pulsed on for 0.1 sec and was then off for 0.2 sec; the pulsing sequence was: O-lamp only, N-lamp only, both lamps off. The performance of the lamp-spectrometer system was checked before and after each external observation by monitoring the signals in each resonance multiplet reflected from cylinders mounted on the inner surface of the closed instrument door.

Retroreflector reflectivities and the spectrometer-detector response were determined as functions of wavelength in pre-flight calibrations. The resonance lamps were calibrated for absolute flux in each multiplet and several backup units were subjected to a series of line shape studies by a chemical titration-absorption method similar to that of Lin et al. [1970].

Since the spacecraft velocities were considerably greater than the average thermal velocity of the absorbing atoms, the wavelength of the lamp radiation was Doppler-shifted away from resonance with the absorbing species unless the light beam was perpendicular to the orbital velocity vector. This effect was turned to advantage by having the Apollo maneuver slowly past the Soyuz at a fixed range such that the angle between the light beam and the perpendicular to the velocity vector traversed roughly $\pm 15^\circ$. Each

such session of data acquisition required about 10 minutes. Observations were carried out on the night side of three consecutive orbits at spacecraft ranges of 150 m, 500 m, and 1000 m, respectively. Throughout the maneuvers the retroreflector was tracked by means of a modified star tracker and a visual alignment sight so that it would remain in the spectrometer field of view.

The signal in counts/sec arising from the transmission of 130.4 or 120.0 nm resonance radiation through the absorbing medium and reflection from Soyuz at an observation angle θ (relative to the perpendicular to the velocity vector) and at a monochromator wavelength setting, λ , is:

$$S_{\text{TRANS}}(\theta, \lambda) = \frac{K_1}{x^2} \sum_{j=1}^3 I_{oj} T_j^{\text{SLIT}}(\lambda) [1 - A_j(\theta)] \quad (1)$$

where x is the separation of the two spacecraft, I_{oj} is the relative emitted intensity of the j^{th} line of the triplet, $T_j^{\text{SLIT}}(\lambda)$ is the spectrometer slit function for a 1.15 nm bandpass, $A_j(\theta)$ is the fractional absorption of the j^{th} line and K_1 is a collection of constants including the incident lamp flux, the transmission and collection geometry, the mirror and retroreflector reflectivities, and the spectrometer-detector response. The fractional absorption, $A(\theta)$, for a given resonance line can be calculated by assuming a Doppler-shaped absorbing line:

$$A(\theta) = \frac{\int_{-\infty}^{\infty} f(\omega) [1 - \exp(-2xn\sigma_o^T e^{-(\omega - v \sin \theta)^2})] d\omega}{\int_{-\infty}^{\infty} f(\omega) d\omega} \quad (2)$$

where n is the concentration of the absorbing state of the atom, σ_o^T is the absorption cross section for the transition at the absorber temperature, v is the ratio of the orbital velocity to the most probable absorber velocity,

ω is a reduced frequency inversely proportional to the absorber Doppler width, and $f(\omega)$ is the line shape of the emitted resonance radiation. Previous investigations of similar line sources have shown that $f(\omega)$ can be expressed as a self-absorbed, Doppler-broadened line shape with a given optical depth within the lamp and an effective emitter temperature [Kaufman and Parkes, 1970; Lin et al., 1970]. Further work has been done to characterize the line shapes of such sources and will be reported in detail elsewhere [W. T. Rawlins and F. Kaufman, to be published].

The overlap of the outgoing light beams and the field of view of the spectrometer gives rise to a resonance fluorescence contribution to the observed signal. This contribution can be expressed in terms of a parameter x_0 which is the distance from the collecting mirror at which an assumed abrupt filling of the field of view of the spectrometer by resonance fluorescence gives the same integrated overlap of the outgoing beam and the field of view as actually occurs. The overlap may thus be simply expressed in the form $\int_{x_0}^{\infty} x^{-2} dx$, and the resonance fluorescence counting rate is

$$S_{RF}(\theta, \lambda) = \frac{K_2}{x_0} \sum_{j=1}^3 I_{o_j} T_j^{SLIT}(\lambda) A_j(\theta) \quad (3)$$

where K_2 is a collection of constants similar to K_1 in Equation (1).

All the parameters in Equations (1), (2), and (3) were determined either by pre-flight calibrations or by testing of virtually identical backup units, except for the orbital velocity and the temperature and density of the absorbing gas. Although the far-field beam optics cannot be characterized well enough to allow accurate prediction of absolute intensities, relative counting rates as functions of wavelength and observation angle can be computed from Equations (1)-(3) for different assumed atom concentrations and can be compared to the experimental results.

Results

The absorption measurements were carried out on July 19, 1975 after the final spacecraft undocking, before the conclusion of the joint phase of the project. On three successive orbits, beginning with Apollo orbit 60, the two spacecraft executed out-of-plane maneuvers to collect data at ranges of 150 m and 500 m and a final in-plane maneuver at an increasing range of about 1000 m. After the final separation maneuver, the Apollo acquired a full orbit of out-of-plane resonance fluorescence and airglow data and performed a 360° roll maneuver to measure resonance fluorescence background and ambient gas pile-up. Those experiments provided interesting information but only the results of the 150 m and 500 m reflection-fluorescence exercises will be reported here.

No clearly identifiable reflected radiation was observed during the 150 m maneuver, although all systems appeared to be functioning properly. A 130.4 nm signal of about 6000 Hz (apparently OI resonance fluorescence) was obtained, but the signals in the 120.0, 149.3, and 135.6 nm channels were near the background level (≤ 20 Hz), or about 3 orders of magnitude lower than expected. The Soyuz was therefore requested to maneuver so as to allow the use of another retroreflector for the 500 m exercise. Substantial reflected signal was observed in all four wavelength channels during the 500 m maneuver, but the signal decayed during the course of the run. The constancy of the door-closed reflected intensities before and after the 500 m observations suggests that this signal decay was due to deterioration of the reflectivity of the retroreflector. The raw data for atomic oxygen from the two sets of observations are shown in Figure 2. The asymmetric and flat θ dependence of the 150 m resonance fluorescence can be attributed to wake and ram effects in the near field as the Apollo maneuvered through the sweep.

(This interpretation is buttressed by the results of the 360° roll exercise to be reported in a later publication.) During the 150 m sweep θ changed from negative (field of view in the wake) to positive values (field of view in partial ram). The 500 m sweep was executed in the reverse direction, so that time runs from right to left in Figure 2 for the 500 m data. It can be seen that the 135.6 nm signal decays by a factor of about 6 during the sweep; the 120.0 and 149.3 nm signal (not shown) decayed by about an order of magnitude with a constant ratio, from 400 and 350 Hz at $\theta = 8^\circ$ to near the background count rate at $\theta = 0^\circ$. The 130.4 nm signal does not track the 135.6 nm signal because of the large contribution of resonance fluorescence to the total 130.4 nm signal. If the observed counting rates are corrected for the signal degradation, the resulting values for both resonance fluorescence (from the 150 m run) and reflected signal are about a factor of 5 to 9 lower than can be calculated using the pre-flight calibration results, probably because of beam inhomogeneity in the far field. Consequently, we have analyzed the data using relative signal counting rates.

Analysis

The variation with θ of the transmitted signal at 500 m was determined by subtracting the resonance fluorescence contribution observed in the 150 m exercise from the total signal obtained in the 500 m observation and normalizing that difference to a constant value of the counting rate at the reference wavelengths (135.6 or 149.3 nm). The experimental OI ratios of 130.4 nm to 135.6 nm counting rates are shown in Figure 3. In the case of the nitrogen data, the resonance fluorescence signal in the 150 m experiment is negligibly small. During the 500 m exercise, the ratio of 120.0 nm to 149.3 nm is about 1.1 and is independent of θ within the experimental error. In order

to determine the absolute values of the transmitted intensities for comparison to the resonance fluorescence signal, the transmitted/reference ratios were multiplied by the initially observed counting rates for the 135.6 nm (2500 Hz) and 149.3 nm (350 Hz) reference signals. The observed relative count rates were compared to calculated values using Equations (1)-(3) and various atom densities. The orbital velocity was 7.8 km s^{-1} and the local gas temperature, determined from the 10.7 cm solar flux and the Ap index, was 777 K. ($F_{10.7}:81.8$; $F_{10.7}^{(AV)}:73.0$; $A_p:9.0$). In the case of the 150 m data the latitude, longitude and local time changed from -1.4° , 108° and $23^{\text{h}}16^{\text{m}}$ to -7.2° , 113° and $23^{\text{h}}36^{\text{m}}$ as θ varied from 0 to 10° . At 500 m these coordinates varied from -15.90° , 96° and $00^{\text{h}}02^{\text{m}}$ to -27° , 106° and $00^{\text{h}}46^{\text{m}}$ as θ varied from $+10^\circ$ to 0° .

The oxygen results were analyzed in three different ways. First, the shape of the $S_{\text{TRANS}}(\theta)$ data was compared to calculated curves, as shown in Figure 3. This curve fitting shows the data to be consistent with the range $[0] = (1.2 \pm 0.5) \times 10^9 \text{ cm}^{-3}$. Second, the slope of the most precise data, between θ values of 4° and 8° , was fitted to calculated values. This procedure gave $[0] = (1.15 \pm 0.36) \times 10^9 \text{ cm}^{-3}$. Third, the ratio of the corrected transmitted signal at $\theta = 8^\circ$ to the resonance fluorescence signal at $\theta = 0^\circ$ was compared with calculated values, with the result $[0] = (1.15 \pm 0.06) \times 10^9 \text{ cm}^{-3}$. The agreement among these methods confirms the validity of the assumptions made in interpreting the raw data. We conclude that the oxygen density measured in the experiment is $[0] = 1.15 \times 10^9 \text{ cm}^{-3}$ with an overall accuracy of $\pm 30\%$.

The nitrogen data were analyzed using the ratio of the transmitted (500 m) signal to the resonance fluorescence (150 m) signal. The 120.0 nm counting rate at 150 m was evaluated by averaging the signal and background

counting rates over the entire period of data acquisition; the net signal at 120.0 nm was only (6.5 ± 1.3) Hz. If it is assumed that this signal is entirely due to resonance fluorescence, the corresponding nitrogen density is $[N] = (9.1^{+2.1}_{-1.4}) \times 10^6 \text{ cm}^{-3}$. A trace amount of 135.6 nm signal from the O lamp at 150 m suggests that as much as 1.6 ± 0.5 Hz of this 120.0 nm signal may be reflected N lamp radiation. Unless further analysis proves otherwise, this means that the nitrogen density may actually be as low as $[N] = (7.0^{+2.6}_{-1.4}) \times 10^6 \text{ cm}^{-3}$. We conclude that the measured nitrogen density lies in the range $5.6 \times 10^6 \text{ cm}^{-3} \leq [N] \leq 11.2 \times 10^6 \text{ cm}^{-3}$.

Discussion

Our result for the atomic oxygen density near midnight at 220 km agrees rather well with old mass spectrometric results for similar solar conditions [Hedin et al., 1964; Hedin and Nier, 1966]. It is slightly lower than the midnight value reported by Newton et al. [1975], as might be expected because of the different solar conditions ($F_{10.7}$ of 110 compared to 73 on July 19, 1975). It is in good agreement with recently reported summertime mass spectrometric measurements by Atmosphere Explorer-C [Nier et al., 1976; Mauersberger et al., 1976a]. From data obtained by AE on the day of the ASTP observations and extrapolated from 350 km the predicted oxygen density of $0^{\text{h}}46^{\text{m}}$ and -27° latitude and 225 km was $1.4 \times 10^9 \text{ cm}^{-3}$ (private communication, G. Carignan). Our atomic nitrogen result is in good agreement with the results of Torr et al. [1975], who inferred $[N]$ from nighttime AE-C measurements of ionic and neutral constituents, and is consistent with both the extrapolated nighttime AE-C mass spectrometric measurements of Mauersberger et al. [1975, 1976b] above 400 km and the twilight NO δ -band emission results of Feldman and Takacs [1974] at 140 km.

Daytime measurements of NO by γ -band fluorescence [Rusch et al., 1975] and N by $N(^2D)$ dayglow [Rusch et al., 1975; Torr et al., 1976] and mass spectrometry [Mauersberger et al., 1975, 1976b] suggest daytime N densities a factor of 2 to 5 higher than the above nighttime measurements and daytime NO densities of $\sim 8 \times 10^5 \text{ cm}^{-3}$ near 225 km. Two recent models of thermospheric odd nitrogen aeronomy [Strobel et al., 1976; Ogawa and Kondo, 1976] predict stronger diurnal variations of N ($[N] \sim 10^6 \text{ cm}^{-3}$ or less at night at 225 km), with nighttime NO densities near 10^7 cm^{-3} at 100 km and decreasing at higher altitudes; the value of $[N]$ is critically dependent on the NO density since N and NO mutually destroy each other. Recent observations of NO near midnight in the tropics [S. K. Atreya, T. M. Donahue and B. Wasser, private communication, 1976] from OAO Satellite Copernicus using a UV stellar occultation technique [Atreya et al., 1976] indicate that such NO densities are too large. According to the Copernicus observations, the NO density is less than 10^6 cm^{-3} at all altitudes above 90 km; this observation is compatible with the larger nighttime N densities reported here.

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Figure Captions

Figure 1. Schematic diagram of optical transmitting and collecting system on Apollo.

Figure 2. OI signal vs. observation angle for the 150 m and 500 m experiments.

Figure 3. Ratio of transmitted to reference signals vs. θ for 0. The curves were calculated for the oxygen densities shown. v is the orbital velocity, T_G is the kinetic temperature of the absorbing gas, and T_L is the effective emitter temperature in the lamp.

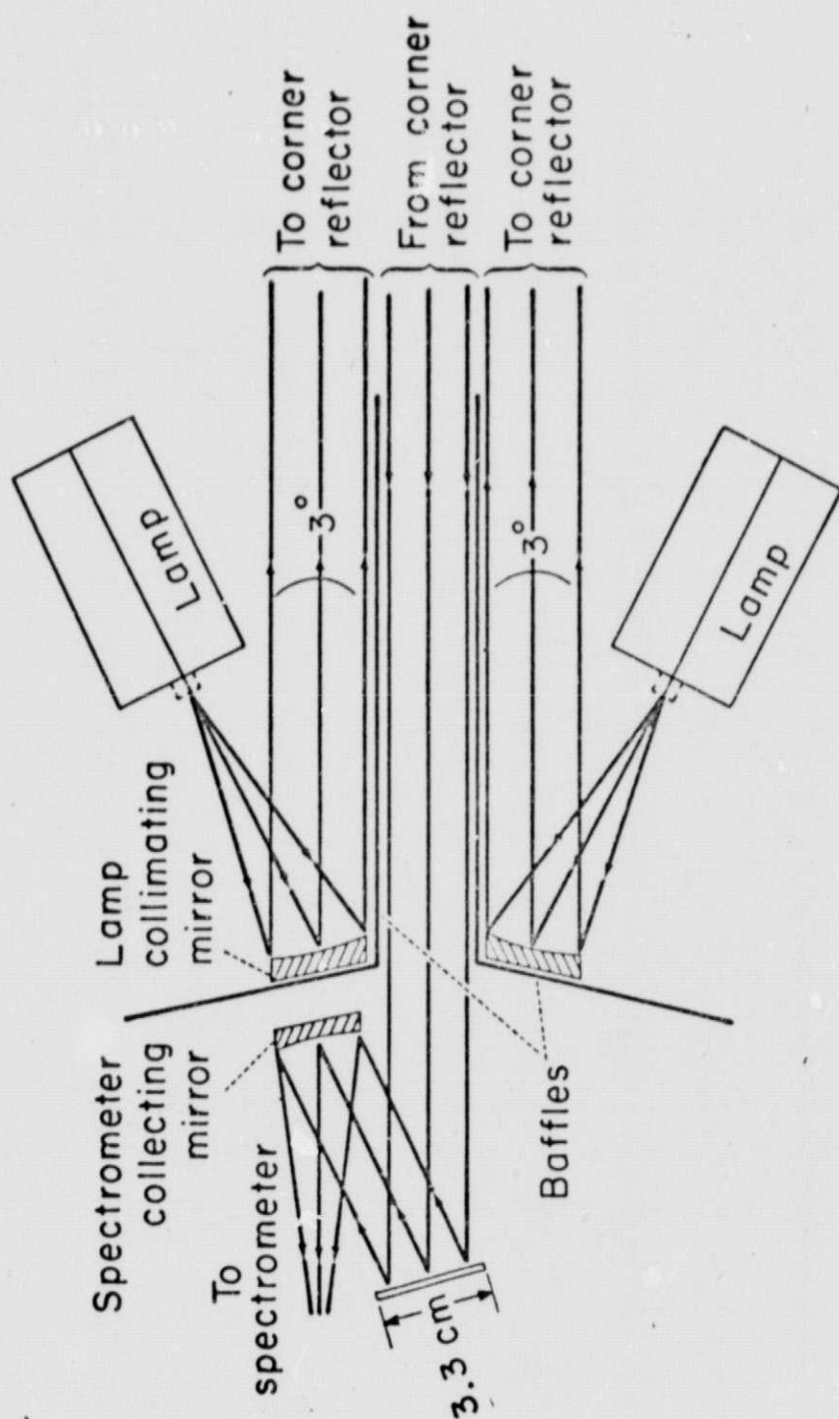


Figure 1

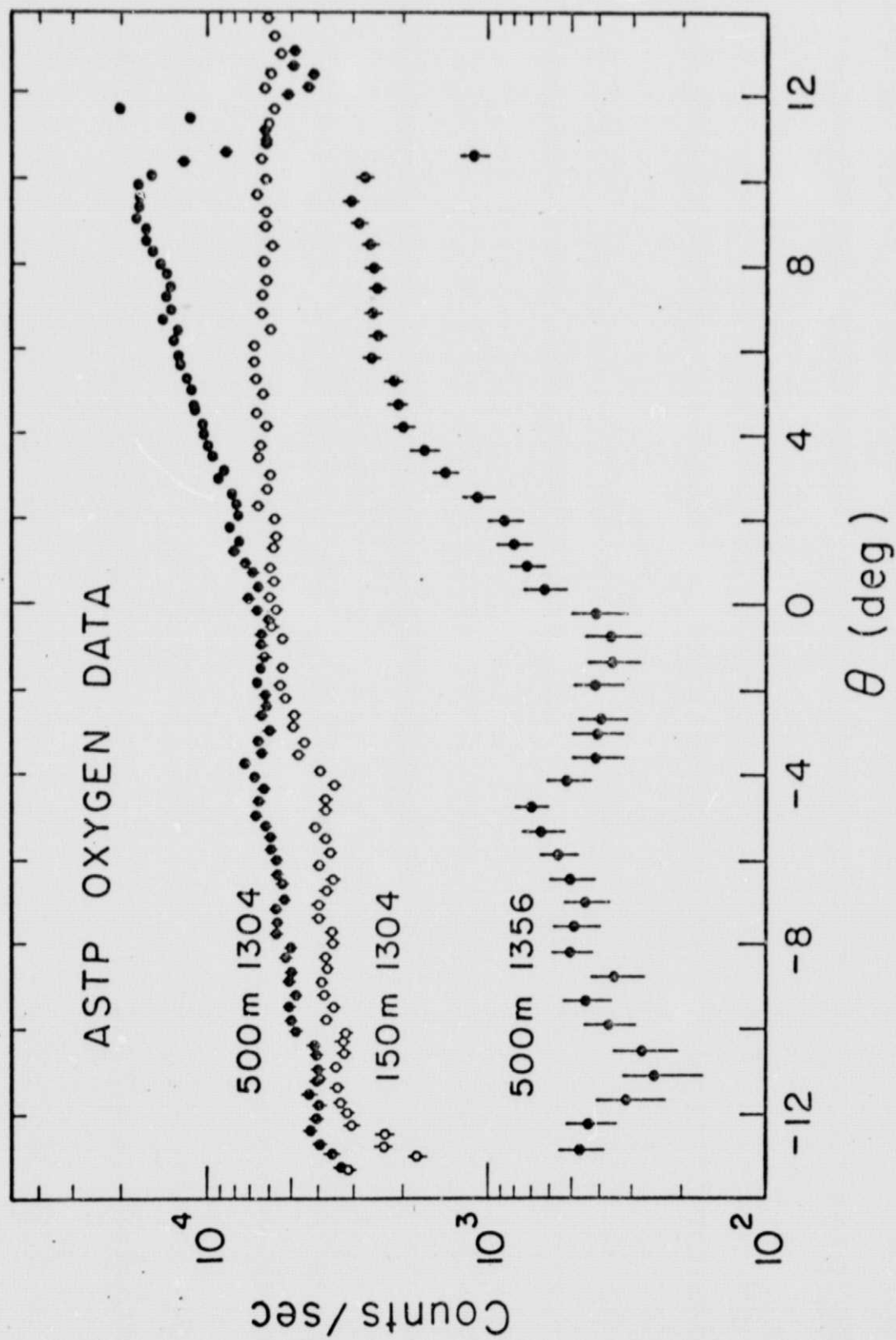


Figure 2

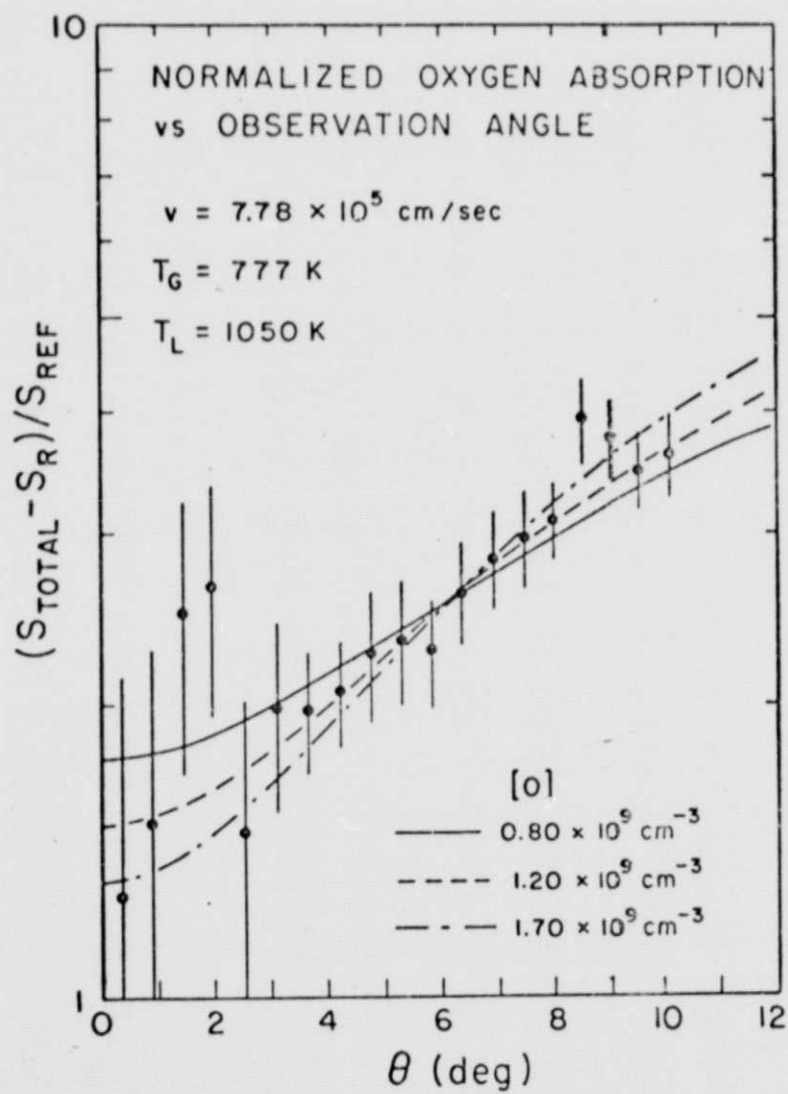


Figure 3